NATO LECTURES

M. Meyyappan

Commercialization of Nanotechnology

Abstract

Nanotechnology is an enabling technology and as such, will have an impact on electronics, computing, data storage, communications, materials and manufacturing, energy, environment, transportation, health and medicine, national security and space exploration. This lecture will cite examples in each of these sectors and present a forecast of short term (< 5 years), medium term (10 years) and long term (> 15 years) prospects. In addition, the challenges currently being faced to commercialize nanotechnology will be discussed in detail. A summary outlining efforts across the world in terms of commercialization, startup activities, participation of major multinational corporations, government funding etc. will be presented.

It is important to recognize that nanotechnology is not any one technology or a one-sector technology. Its reach is extremely broad: electronics, computing, data storage, communications, aerospace, materials, manufacturing, health, medicine, energy, environment, transportation and national defense. In that sense, it is an enabling technology.

In the electronics and computing, we can expect processors with million times better performance than the state-of-the-art with less power consumption, multi-terabit storage in small mass devices, and quantum computing from advances in nanotechnology. Also, it is possible to envision integration of logic, memory and sensing on the same chip. In the nearer term, one major area to benefit from nanotechnology is field emission devices for large area flat panel devices.

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In the materials sector, the major focus is on high strength, low weight composites enabled by nanomaterials. Other characteristics researchers are currently paying attention include multifunctionality and self-healing. Biologically-inspired materials are also receiving much attention and examples include synthetic gecko, and self-cleaning glass (inspired by the lotus flower).

In health and medicine, the biggest impact can come from fast gene sequencing devices. A nanopore based technology appears to have the potential to sequence the entire human genetic makeup in less than two hours. This advance would enable ‘individualized medicine’. Other possibilities include effective drug delivery approaches, early warning sensors for serious illnesses, rejection-proof artificial ligaments, bones and other parts.

In the energy sector, while the major focus is on how nanomaterials can improve the long standing efficiency problems in solar and other alternative energy sources, the most significant benefit may well be in the energy utlilization. The conventional filament light bulbs, though inexpensive, are very energy inefficient. Solid state lighting in contrast is extremely energy efficient. Current efforts include novel materials and processes to make this technology cost-competitive.

The transportation sector would benefit from high strength, low weight composites for increased fuel efficiency, wear-resistant tires, advanced sensors for hydrogen based economy, efficient catalytic converters with reduced use of expensive noble metals like platinum, and wear-resistant coatings. In the environment sector, the large surface area of nanomaterials, translated into high adsorption rates, can help with waste remediation, pollutant conversion, other environmental cleanup operations, high efficiency filters and membranes.

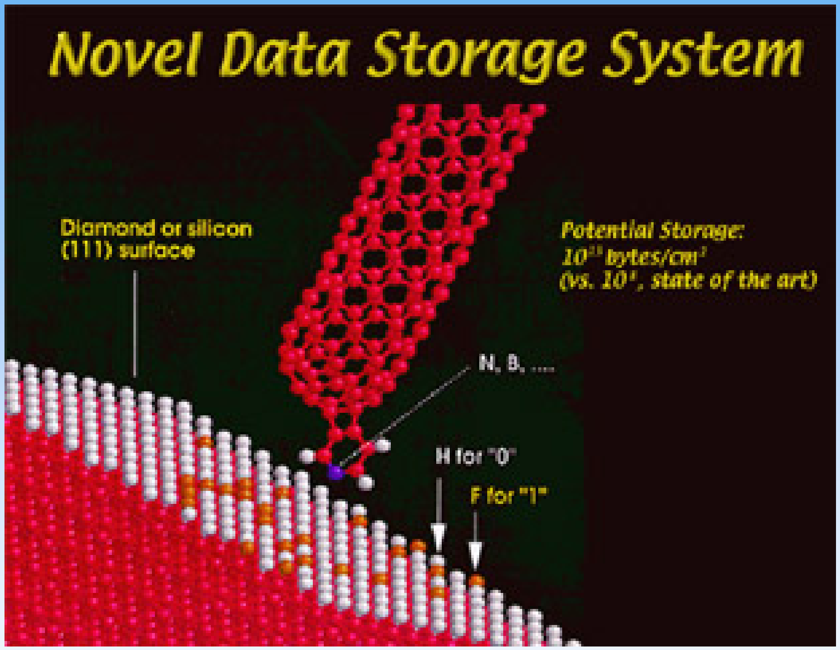
As summarized above, the potential of nanotechnology in various sectors is promising. While there are some niche applications where nanotechnology products have just penetrated the market, the major impact will be at least a decade away. Currently there are a few cosmetic products incorporating nanoparticles on the market such as suntan lotions, eye liners, and flat irons. Automotive companies have mixed small quantities of carbon nanotubes in the process of making fenders to render them electrically conducting so that the parts can be painted inexpensively in electrochemical baths. Stain resistant cotton coated using novel processes is currently used in textile manufacturing.

In the short term (< 5 years), commercial impact may include flat panel displays, nanoparticles in cosmetics, nanoparticles in automotive applications such as body moldings, engine covers, and catalytic converters, nanoparticles in catalyst and inkjet markets and tools. In the medium term, memory devices, biosensors for diagnostics, advances in lighting, advances in gene sequencing, are all possible. Routine use of nano composites in automotive and aerospace industries is a long term prospect as these are risk-averse sectors and extensive testing and characterization alone takes significant time. Nanoelectronics beyond silicon according to Moore's Law is also a long term endeavor.

Nanotechnology: Commercialization

M. Meyyappan

Impact of Nanotechnology

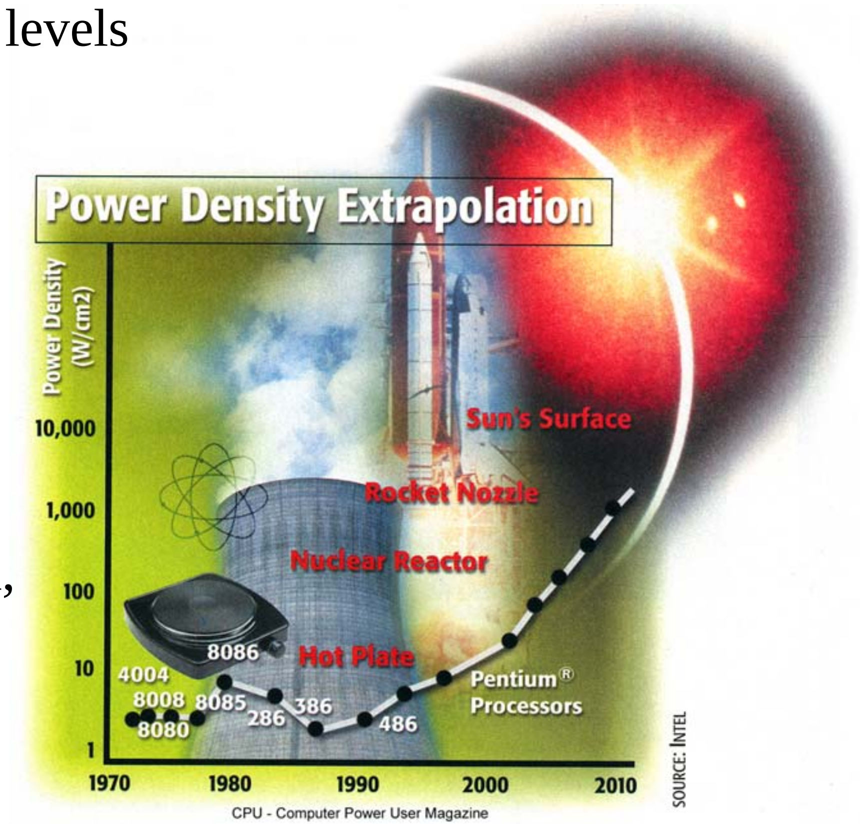


Nanotechnology is an enabling technology

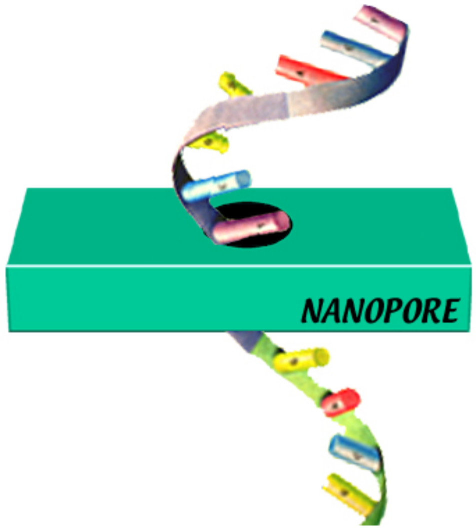
- Computing and Data Storage
- Materials and Manufacturing
- Health and Medicine
- Energy
- Environment
- Transportation
- National Security
- Space exploration
-
-

Expected Nanotechnology Benefits in Electronics and Computing

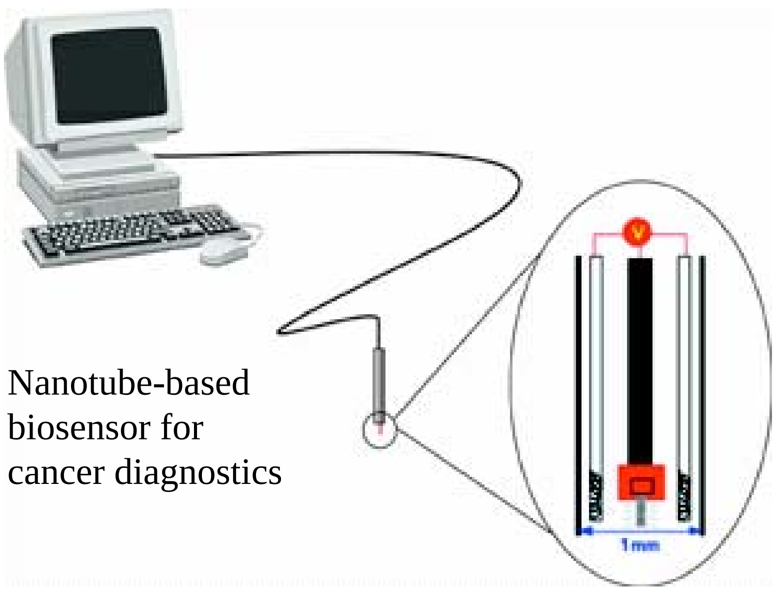
- Processors with declining energy use and cost per gate, thus increasing efficiency of computer by 10^6
- Small mass storage devices: multi-tera bit levels
- Integration of logic, memory and sensing
- Higher transmission frequencies and more efficient utilization of optical spectrum to provide at least 10 times the bandwidth now
- Integration of IT network, communication, sensing, Ex: intelligent appliance
- Display technologies
- Quantum computing



- Expanding ability to characterize genetic makeup will revolutionize the specificity of diagnostics and therapeutics
  - Nanodevices can make gene sequencing more efficient



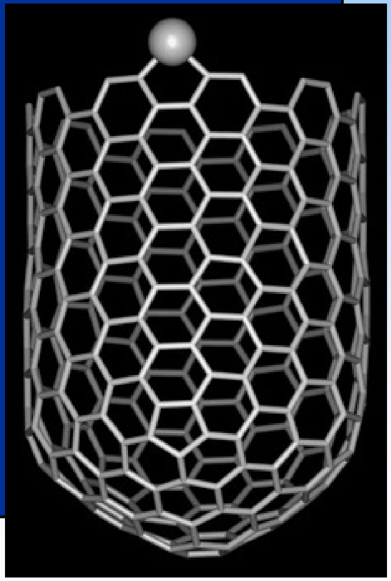
- Effective and less expensive health care using remote and in-vivo devices



Nanotube-based biosensor for cancer diagnostics

- New formulations and routes for drug delivery, optimal drug usage
- More durable, rejection-resistant artificial tissues and organs
- Sensors for early detection and prevention

- Ability to synthesize nanoscale building blocks with control on size, composition etc. → further assembling into larger structures with designed properties will revolutionize materials manufacturing
  - Manufacturing metals, ceramics, polymers, etc. at exact shapes without machining
  - Lighter, stronger and programmable materials
  - Lower failure rates and reduced life-cycle costs
  - Bio-inspired materials
  - Multifunctional, adaptive materials
  - Self-healing materials



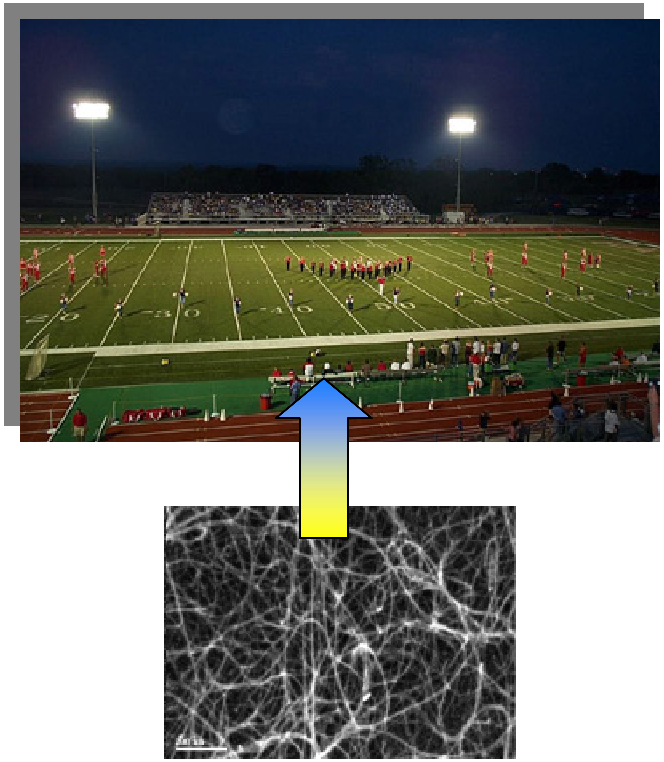
Energy Production and Utilization

- Energy Production
  - Clean, less expensive sources enabled by novel nanomaterials and processes
  - Improved solar cells
  - *In-situ* refinery and gasoline out of well

- Energy Utilization
  - High efficiency and durable home and industrial lighting
  - Solid state lighting can reduce total electricity consumption by 10% and cut carbon emission by the equivalent of 28 million tons/year (Source: Al Romig, Sandia Lab)
- Materials of construction sensing changing conditions and in response, altering their inner structure

Benefits of Nano in the Environment Sector

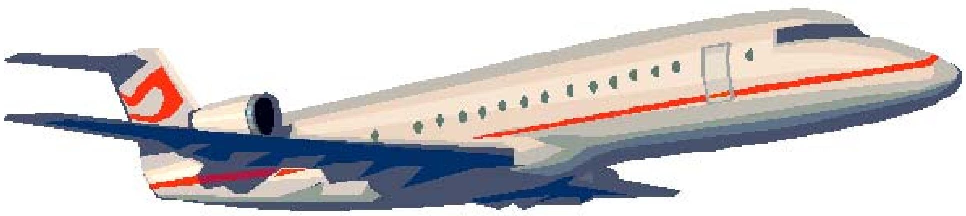
- Nanomaterials have a large surface area. For example, single-walled carbon nanotubes show ~ 1600 m^2/g. This is equivalent to the size of a football field for only 4 gms of nanotubes. The large surface area enables:
  - Large adsorption rates of various gases/vapors
  - Separation of pollutants
  - Catalyst support for conversion reactions
  - Waste remediation



- Filters and Membranes
  - Removal of contaminants from water
  - Desalination
- Reducing auto emissions, NO_x conversion
  - Rational design of catalysts

Benefits of Nanotechnology in Transportation

- More efficient catalytic converters
- Thermal barrier and wear resistant coatings
- Battery, fuel cell technology
- Wear-resistant tires



- Improved displays
- High temperature sensors for 'under the hood'; novel sensors for "all-electric" vehicles
- High strength, light weight composites for increasing fuel efficiency

- Improved collection, transmission, protection of information
- Very high sensitivity, low power sensors for detecting chem/bio/nuclear threats
- Light weight military platforms, without sacrificing functionality, safety and soldier security
    - Reduce fuel needs and logistical requirements
- Reduce carry-on weight of soldier gear
    - Increased functionality per unit weight

Assessment of Opportunities

- **Short term (< 5 years)**
    - Nanoparticles
        * Automotive industry (body moldings, timing belts, engine covers…)
        * Packaging industry
        * Cosmetics
        * Inkjet technology
        * Sporting goods

    - Flat panel displays
    - Coatings
    - Tools
    - Catalysts (extension of existing market)
    - CNT-based probes and sensors

Assessment of Opportunities (Cont.)

- **Medium term (5-10 years)**
  - Memory devices
  - Fuel cells, batteries
  - Biosensors (CNT, molecular, qD based)
  - Biomedical devices
  - Advances in gene sequencing
  - Advances in lighting
- **Long term (> 15 years)**
  - Alternatives to silicon CMOS
  - Routine use of novel nano composites in Aerospace, automotive (risk-averse industries)
  - Gasoline our of oil wells
  - Many other things we haven’t even thought of yet

Current Status of Commercialization

1. Electronics / Computing / Communications
   - Molecular electronics / memory devices: Zettacore, HP
   - Nanotube electronics: IBM, Intel
   - Nanowire based devices: Nanosys, Nantero

2. Displays based on nanotube field emission: Samsung, number of Japanese companies, Taiwanese companies

3. Solar cells: Nanosys, Matsushita, Nanosolar

4. Nanotube production: CNI, Ahwanee, number of Japanese and Chinese companies

5. Nanoparticles: Degussa….

6. Nanoparticles in cosmetic applications: sunscreen lotions, eyeliners, flat irons….

7. Addition of nanotubes to make automotive fenders and panels slightly conducting in order to paint them in electrochemical vats.

Current Status of Commercialization (cont.)

8. Rational design & production of catalysts, catalytic converters: Nanostellar

9. Stain-resistant fabrics: Nano Tex

10. Novel lithographic processes

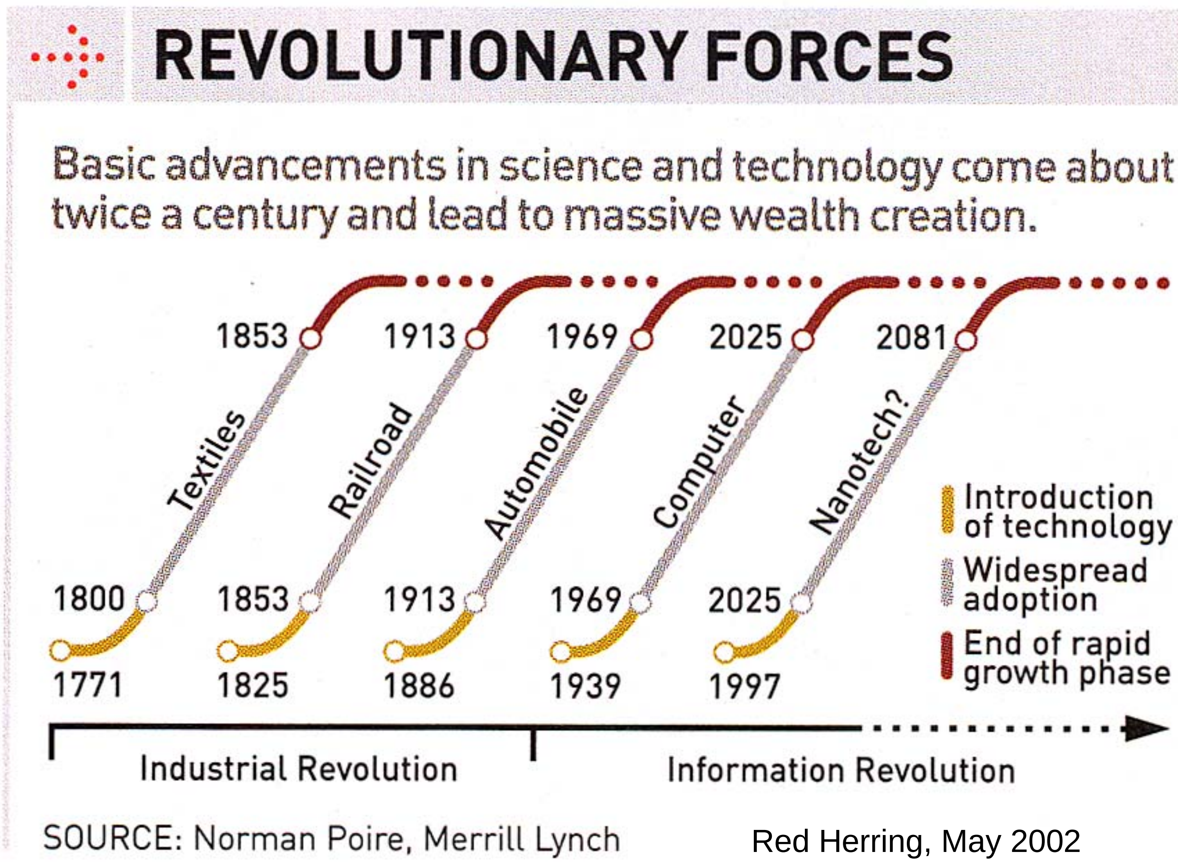
11. Fuel additives (cerium oxide nanoparticles) to reduce fuel consumption/ pollution: Oxonica (UK)

12. Lithium ion batteries: several Japanese companies, NanoExa

13. Thermal management: Nanoconduction

This is not an exhaustive list.

Revolutionary Technology Waves



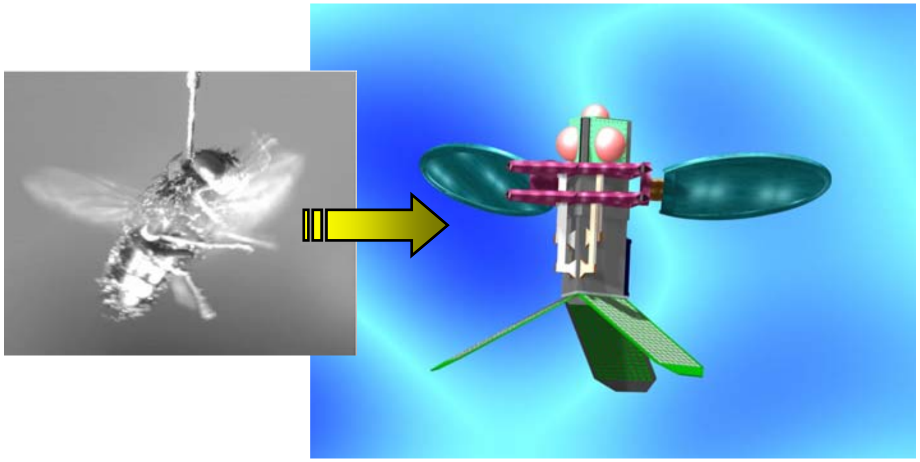
Red Herring, May 2002

Commonality: Railroad, auto, computer, nanotech
all are enabling technologies

Challenges facing Nanotechnology

- Lots of nanoscience, very little nanotechnology now; more emphasis on technology development and participation from engineering communities are urgently needed
- **People do not buy technology; they buy products**
  - Robust product development is critical to realize the potential
- Recognition of nano-micro-macro hierarchy in product development
- What is the right Nano Business Model?
  - Can we afford to copy the Bio-sector?
  - IP → IPO?, Product → IPO?

Source: UC Berkeley



Challenges facing Nanotechnology (Continued)

- It simply takes 10 or more years to bring out a product from the lab
- Role of the Government: Given the long term nature of the technology and payoffs in terms of job creation and economic returns,
  - Lack of patience from Federal Government will kill the field
  - But history indicates, Federal agencies have been responsible for numerous technology wins in the last 50 years
  - So, governments should ignore the hype, be patient and stay the course for the long run
- Venture community behavior will determine the fate
  - Lack of patience will hurt the startup activities
  - Indiscriminate investment like in the dotcom days will seal the field
- Early and periodic wins, a must to keep investor confidence high
- Need some sanity in issuing patents

Challenges Facing Nanotechnology (continued)

- Most startups have limited funding and cannot afford expensive characterization equipment (SEM, TEM, AFM, STM....)
  - Unless university-affiliated, access to equipment is very difficult
  - Even with fee-for-use access to university facilities (ex: NNI user facilities), waiting period for access is long since thesis/education work is the highest priority
- Shared use facilities in Incubator settings, a watering-hole approach
- Educating future generation scientists and engineers

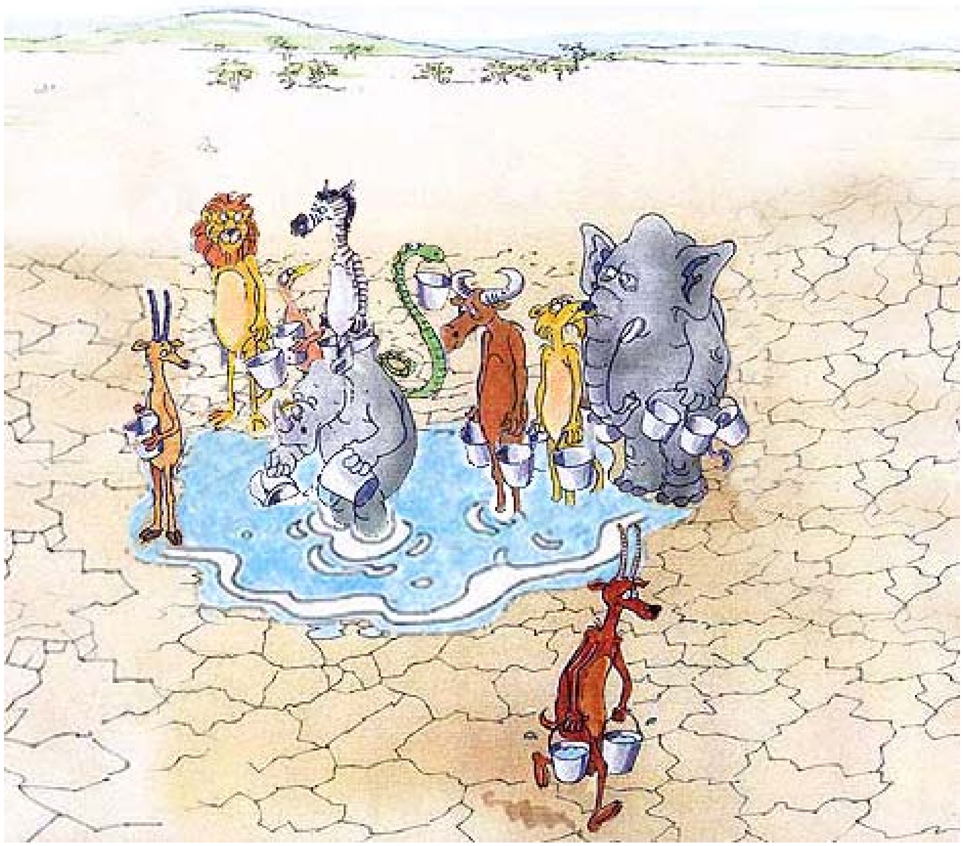


Image courtesy of: www.tecknarstugan.com/ miljo.html

USA vs. Rest of the World

- Japan, EU funding for Nano is comparable to that in U.S. or higher
- Strong activities in Korea, Taiwan, Singapore, Switzerland, China
  - Not much blue-sky research but much sharper focus
- ‘Majors’ play a major role in other countries
  - Financial staying power
  - Long term approach
  - No quarterly pressures though that is changing
- Fortunately in the U.S. also, the ‘Majors’ have started to take notice
  - Just can’t rely on start-ups, only a very few of them ever make it

Safety and Health Concerns: Regulatory Issues

- All are real concerns but everything is getting overblown
- "Knowledge is power." So, we need to know the impact of nanomaterials with respect to: worker safety, public safety, etc.
  - This requires all the studies normally done with any new material development.
  - Only such knowledge can lead us to see if new regulations and congressional legislation are required
- But, why is this any different from the past? Why make an unnecessarily big deal about nano?
- Would (name your favorite company here) do anything different in bringing a nanomaterial to market? They are still bound by Federal/State/Local safety and health guidelines, fear of lawsuits….
- Let us be realistic: We have been burning coal for about 200 years if not more. We can't seem to agree on anything related to the impact on air quality, acid rain, climate change, increased asthma among children, more lakes off-the-list for fresh water fishing (mercury poisoning)….
  - Societies have always moved on with developments (unless something is totally worrisome/disastrous, which is doubtful here) and addressed issues along the way….

Summary

- Nanotechnology is an enabling technology that will impact electronics and computing, materials and manufacturing, health, medicine, energy, transportation…
- Opportunities and rewards are great and hence, tremendous worldwide interest
- Integration of this emerging field into engineering and science curriculum is important to prepare the future generation of scientists and engineers